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14. ABSTRACT
DURIP funds were used to purchase three cryopumps, a state-of-the-art tunable-diode laser, a dye-to-Ti:sapphire conversion kit for a ring laser (for enhanced IR capability), and a commercial ion-sputtering source. The new cryopumps increased the xenon pumping speed of the Large Vacuum Test Facility (LVTF) at the University of Michigan's Plasmadynamics and Electric Propulsion Laboratory (PEPL) from 140,000 to 240,000 l/s. The new lasers will be used in conjunction with our tunable ring laser to make Two-Wavelength Simultaneous Laser Induced Fluorescence (TWSLIF) measurements for Hall thruster discharge channel erosion characterization. TWSLIF will first be demonstrated in a smaller vacuum facility with a commercial ion source and a boron nitride substrate. Once perfected in the smaller chamber, TWSLIF will be used in the LVTF to characterize discharge channel erosion of the P5 Hall thruster. This capability will not only enhance PEPL, but will establish a national facility where thruster erosion and spacecraft integration issues are investigated.

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Establishing a Facility for Making Non-Intrusive, Near-Real-Time Electric Propulsion Thruster Erosion Measurements via Simultaneous Two-Frequency Laser Induced Fluorescence

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Introduction

Propulsion systems having high exhaust velocities (Ve>10 km/s) are desirable for a variety of space missions. In order for a propulsive system not to require an inordinate amount of propellant, its exhaust velocity should be of the same order as or greater than the characteristic velocity increment (Delta-V) required for a given space mission. Studies have shown that for orbit transfer missions of interest by NASA and the DoD, a characteristic velocity increment of over six kilometers per second may be necessary[1]. Furthermore, experience gleaned from operation *Desert Storm* shows the need for military space assets to be rapidly repositioned without excessive use of onboard propellant; *i.e.*, the need for high specific impulse propulsion systems of moderate thrust.

Cryogenically-fueled chemical rockets, which rely on the intrinsic energy available from the chemical reactions of their constituent propellants, are inherently limited to exhaust velocities below 5 km/s.[2] Chemical rockets which use space storable propellants such as hydrazine are limited to exhaust velocities of about 3 km/s.[2] Thus, propulsion systems which produce exhaust velocities considerably higher than those obtained with chemical systems would greatly enhance a variety of orbital space missions.

Ideally, an engine which would be used as the primary source of propulsion for satellite station-keeping and orbit repositioning in modern spacecraft should produce an exhaust velocity between 10 and 25 km/s.[3] To achieve this performance, a propulsion system must accelerate its propellant gas without relying on energy addition through chemical reactions. One approach is the application of electrical energy to propellant in the form of electrical heating and/or electric and magnetic body forces. This type of propulsion system is commonly known as electric propulsion (EP).

EP can be categorized into three groups[4]: i) *Electrothermal Propulsion Systems* in which a gas is electrically heated, either with resistive elements or through the use of an electric arc, and is subsequently expanded through a supersonic nozzle to produce thrust; ii) *Electromagnetic Propulsion Systems* which use electromagnetic body forces to accelerate a highly-ionized plasma; and iii) *Electrostatic Propulsion Systems* which use electric fields to accelerate ions.

In addition to possessing suitable exhaust velocity, an EP system must also be able to convert onboard spacecraft power into directed kinetic power of the exhaust stream efficiently (*i.e.*, possess high thrust efficiency) and must generate suitable thrust to ensure reasonably short deployment times.

Electrothermal systems have limited utility for this role because of performance constraints placed on them by excessive frozen flow and electrode losses[5,6,7]. The specific impulse and thrust efficiency of arcjets operating on standard space-storable propellants (*e.g.*, hydrazine) is limited to less than 650 seconds and 41%, respectively. Recent Air Force arcjet tests have demonstrated specific impulses of over 800 seconds on ammonia. Steady-state electromagnetic systems have demonstrated high thrust efficiencies only at power levels that far exceed those generated onboard current or anticipated spacecraft[8,9]. Gridded electrostatic engines (*e.g.*, ion thrusters), which can achieve large exhaust velocities (Ve>50 km/s) at high thrust efficiencies (>70%), have traditionally demonstrated efficient performance at exhaust velocities above 30 km/s[4,10,11]; beyond the desired range for orbit transfer missions[3]. The high specific impulse of the ion thruster means that for a given spacecraft power level, it will generate less thrust than a lower Isp counterpart, resulting in larger trip times and a demand for longer thruster life. Furthermore, ion thrusters pay a penalty for its high power processing specific mass due to its large operating voltages (*e.g.*, 1100 V) and are limited in thrust density by space-charge effects, making ion thrusters considerably bulkier than other EP systems[4].

Therefore, the ideal propulsion system for orbit transfer missions and for satellite station-keeping is a compact engine of high thruster density that efficiently accelerates propellant (*e.g.*, through electrostatic means) to modest exhaust velocities while requiring discharge voltages of less than 1000 V. As is shown below, the Hall thruster is a device which fulfills these requirements.

The Hall Thruster

The Hall thruster is an electrostatic engine that was developed in the 1960s to alleviate the thrust density limitation of ion thrusters that results from space-charge effects within the acceleration volume. Hall thrusters were also attractive from the standpoint that since grids are not required to accelerate ions, they do not suffer from the large grid erosion rates of ion thrusters. Interest in the Hall thruster waned in the early 1970's, however, because of budgetary cuts and because American researchers were never able to demonstrate that these engines could operate at thrust efficiencies near those achieved with ion thrusters[12,13,14]. As such, Hall thruster research essentially disappeared in the U.S. between 1972 and 1985. From 1985 to 1990, Ford Aerospace (now Space Systems/Loral), in conjunction with the NASA Lewis Research Center (now the John Glenn Research Center at Lewis Field [GRC]), funded a small research effort to determine if Hall thrusters could be used for North-South station-keeping (NSSK)[15,16]. This program proved to be unsuccessful and was abandoned.

Throughout this period, however, Hall thruster research flourished in the Soviet Union, ironically partly because Soviet engineers were never able to develop adequate grids for ion thrusters. Hall thrusters were first tested in space in 1971 with immediate success[16,17]. Since then, over one hundred Hall thrusters have been used on Soviet and Russian spacecraft, mostly as plasma contactors and for East-West station-keeping. However, in 1994 the first satellite to use Hall thrusters for North-South Stationkeeping (NSSK) was launched by Russia. Because of this and numerous experiments which show that Russian Hall thrusters are capable of generating specific impulses of 1500-2200 seconds at thrust efficiencies of 50% or more[18], there has been a great deal of interest in using these engines on American spacecraft for NSSK and for orbit repositioning. For example, the Ballistic Missile Defense Organization (BMDO) in conjunction with NASA GRC and the Naval Research Laboratory (NRL) developed a flight experiment that used a Russian Hall thruster on a U.S. experimental satellite[19]. Space Systems/Loral (SSL) has announced that its next generation of communication satellites will use Hall thrusters for NSSK, perhaps as early as next year (2000). Clearly this device, with performance far superior to that of arcjets, and which is better-suited for Earth orbit missions than gridded ion thrusters[1], currently the most advanced propulsion system used on American spacecraft, would not only serve as an excellent thruster for orbit station-keeping and repositioning roles, but potentially could be scaled in power to propel orbit transfer vehicles and future planetary probes. Thus, GRC has recently issued two contracts for the development of two-stage Hall thrusters with performance equivalent to that of the NSTAR ion thruster flown on NASA's 1998 Deep Space 1 mission.

The Closed-Drift Hall Thruster

There are two types of Hall thrusters that have been studied at great lengths; the end-Hall thruster and the closed-drift thruster (CDT). Both engines, in principle, are capable of producing specific impulses in excess of 1500 seconds with xenon at a thrust efficiency of 50% or greater. However, it is the CDT, which has been developed and used in the former Soviet Union over the past forty years, that is of the most interest to the Western space technology community.

The CDT is a coaxial device in which a magnetic field that is produced by an electromagnet is channeled between an inner ferromagnetic core (pole piece) and outer ferromagnetic ring (Fig. 1). This configuration results in an *essentially* radial magnetic field with a peak strength of a few hundred gauss. This field strength is such that only the electrons are magnetized. In addition, an axial electric field is provided by applying a voltage between the anode and the downstream cathode. As the electrons stream upstream from the cathode to the anode, the **ExB** action on the electrons cause them to drift in the azimuthal direction, forming a Hall current. Through collisions, these electrons ionize propellant molecules that are injected through the anode and which are subsequently accelerated by the axial electric field. The mixture of electrons and ions in the acceleration zone means that the plasma is electrically neutral, and as such, is not space-charge limited in ion current (thrust) density. Since the magnetic field suppresses the axial mobility of the electrons while exerting essentially no effect on ion dynamics, the plasma can support an axial electric field

with a potential difference close to the applied voltage between the electrodes. Thus, the bulk of the ions are accelerated to kinetic energies to within 85% of the applied discharge voltage[12]. This combination of processes accounts for the CDT's high thrust efficiency.

Russian CDTs come in two variants; the stationary plasma thruster (SPT) (also known as the magnet layer thruster) and the anode layer thruster (TAL). The main difference between these two devices is that the SPT uses a dielectric coating that usually contains boron nitride to electrically insulate its acceleration channel while the TAL uses a much shallower channel made out of refractory metals. Performance characteristics of both engines are virtually identical. Although they vary in size and input power, CDTs that are currently being considered for NSSK typically operate at discharge voltages of 300 to 350 V, and thruster currents between 4.5 and 10 A, with xenon mass flow rates of 5 to 10 mg/s. As the discussion below will show, the power level (and therefore the current and mass flow rates) which will be needed in the near future will be considerably higher.

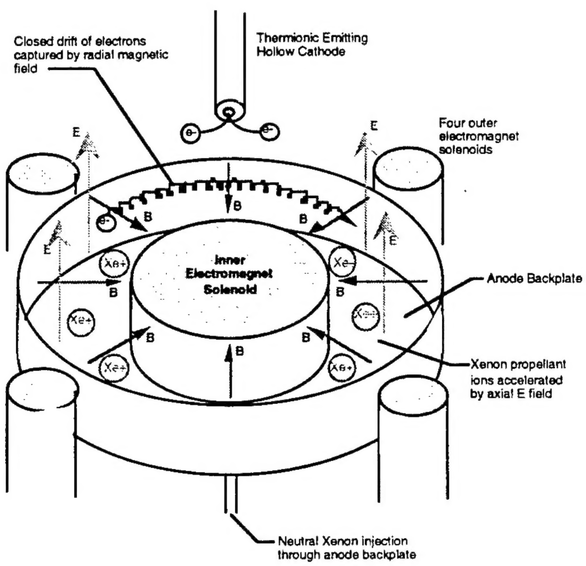


Figure 1: Schematical diagram of a closed-drift Hall thruster.

High-Power Electric Propulsion

Communication satellites are becoming both smaller and larger. This fact is acknowledged throughout the EP community. Hughes Corporation's recent development of the HS-702 satellite with up to 15 kW of solar array power and SS/L's announcement of the 2020 spacecraft with more than 20-25 kW of solar array power by 2003 (nearly twice the power available from today's largest communication satellite) suggests that EP systems will also have to double (or triple) in power from the current 1-3 kW systems. This means that vacuum systems will have to be modified to handle the added propellant flow rates demanded by these higher-power thrusters. The Air Force Research Laboratory (AFRL), GRC, and the Jet Propulsion Laboratory (JPL) have recently upgraded their pumping systems in anticipation of the higher-powered thrusters. Moreover, the fact that the major emphasis of the DoD Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program in EP was on high-power CDTs suggests that the Air Force acknowledges the importance of high-power engines for its future.

Air Force Interest in High-Power Electric Propulsion

With the end of the Cold War, the landscape of global conflict has changed immensely. No longer is surveillance over a fixed region (*e.g.*, the former Soviet Union) adequate for intelligence gathering. Today's intelligence gathering spacecraft must be made more maneuverable and hence easier to re-deploy to be able to respond to a crisis at a moment's notice. After the DoD lost hundreds of millions of dollars of space assets during the Gulf War when reconnaissance satellites ran out of fuel after rapid re-deployment over the Gulf, the DoD – and the Air Force in particular – became committed to using advanced propulsion on their spacecraft. In its recent study entitled "Air Force New Vista 2020," which looked ahead some twenty-five years to predict the future roles and capabilities of the Air Force, the Air Force Scientific Advisory Board listed electric propulsion as one of the key technologies which must be used routinely by the 21st century Air Force.

With the Air Force's desire to develop higher-power, more capable spacecraft for radar-based remote sensing, optical imaging, weather tracking, and communication comes the need for high-performance medium- (2 – 5 kW) and high-power (>5 kW) EP systems for station-keeping and repositioning. That is, the continuing shift to higher-power spacecraft suggests that advanced EP systems are essential in maintaining the Air Force's dominance in space. As noted above, the high efficiency, optimum specific impulse, and high thrust density of the CDT makes it the natural choice for Air Force electric propulsion needs. The recent multi-million dollar award given by the Air Force under the IHPRPT program to an industrial team comprised of SS/L, Atlantic Research Corporation, and the Russian design bureau Fakel for the development of the 5-kW-class SPT-140 CDT attests to the importance of this technology to the defense community. While these and other government-sponsored CDT programs have concentrated on the near-term development aspects of these engines (*e.g.*, life tests and performance validation), until recently little work has been done in performing basic research on how Hall thrusters function and in characterizing the interior plasma and very-near-field (VNF) plume of these thrusters for computer model-building and improving our understanding of the physics associated with these devices. This research must be performed before substantial gains in CDT performance and lifetime can be achieved or long-standing integration issues (*i.e.*, plume divergence and RF interference) can be fully addressed. Although it is our belief that the CDT has the most potential for filling all of the Air Force's electric propulsion needs, we also feel that it is among the least-understood EP systems in existence, particularly to Westerners.

Motivation for DURIP Request

As discussed above, CDTs utilize a complex set of plasma processes to generate thrust at high specific impulse. Although its specific impulse will be considerably higher than that of chemical rockets, its thrust will be much lower, given the fact that the CDT, as is the case of all EP systems, derives its electrical power from the spacecraft. This means that CDTs will have to operate for considerably longer than their chemical propulsion counterparts. Hence long engine life is a premium equal in stature to performance. For example, a CDT used for NSSK of a commercial spacecraft will have to operate for over 5,000 hours over the course of its mission[20,21]. Given the fact that hollow cathodes can operate for more than 20,000 hours, the life-limiter for these engines is discharge chamber wall erosion[21].

As described above, the ions are accelerated by the axial electric field established between the electrodes by the magnetized electrons. To first order, lines of constant potential are parallel with magnetic field lines. Unlike the field lines shown in Fig. 1, magnetic field lines in actuality have non-radial components and bend forward axially[22]. This is particularly true just upstream of the exit plane, and accounts for the high plume divergence exhibited by these engines[23]. The non-radial magnetic field topology implies that some of the ions are accelerated with considerable radial velocities. Since the magnetic field bending occurs upstream of the exit plane, many of these radially accelerated ions will collide with and hence erode the discharge chamber walls (Fig. 2). Not only does this lead ultimately to the end of thruster life once the insulator is completely eroded through, but sputtered-off discharge chamber wall material can redeposit on

and coat spacecraft surfaces such as solar arrays and sensor optics, posing a serious risk to spacecraft operations. This situation is critical to both the SPT and the TAL. While the ceramic insulator of the SPT has a relatively high erosion rate compared to the metal walls of the TAL, metallic coating on spacecraft surfaces, even in lesser amounts, can be more detrimental than insulator deposition.

Before a thruster can be certified for space flight, it must be demonstrated that the engine has sufficient life to perform its mission. Currently, the only way of verifying that a thruster has sufficient life for its mission is to operate it beyond its expected total thrust duration in a vacuum chamber. For example, an SPT-100 was operated for over 5,700 hours and performed nearly 7,000 start cycles at JPL as part of the engine's flight qualification process[21]. JPL also tested an ion thruster continuously for 8,000 hours and is now in the process of testing another ion thruster for 12,000 hours[24]. Though a careful means of ensuring adequate thruster life, thruster life tests suffer from the following shortcomings:

- They are expensive and intensive: Life tests can cost several hundred thousand to millions of dollars, and can tie up valuable vacuum facilities and engineers for several months.

- They allow only *post-facto* bulk analysis: Life tests rarely provide (quantitative) insight into erosion processes. Through post-test inspection (usually destructive), clues are uncovered which may lend themselves to a qualitative understanding of what causes component damage or failure. Witness plates and Quartz Crystal Microbalances (QCMs) may allow for bulk thruster erosion rates to be estimated. However, this technique is extremely difficult to relate to specific thruster component erosion, and is highly susceptible to facility effects;[25] *e.g.*, deposition of sputtered material from the vacuum chamber wall.

- They do not allow near-real-time or time sensitive measurement of erosion. Because information on thruster erosion is obtained by inspecting or dissecting the engine after the test, it is extremely difficult to understand how the erosion rate of a thruster changes with time. For example, the SPT-100 exhibited significant performance variations during its life test[21]. Thruster efficiency dropped from 50% to nearly 42% over the first 1,000 hours of the test, increased over the next 1,000 hours, and slowly decreased to 45% by the end of the test. This behavior is thought to stem from the erosion and the re-deposition of eroded insulator material on the discharge chamber walls. A real-time or near-real-time erosion diagnostic capability would have resolved this issue.

- They are inflexible: Because of the cost and effort associated with them, life tests tend to have rigid operating requirements. Thus, the thruster is usually operated at what is expected to be the most extreme operating condition since the time-insensitive nature of this process does not allow for the understanding of how different operating conditions affect thruster life. The lack of this knowledge may lead to unforeseen problems if what was expected to be the worse case, actually is not.

- They provide little information about spacecraft deposition/erosion rates: A life test would be a natural event to investigate spacecraft integration issues given the long-term nature of the experiment. Long-duration thruster firings should lead to better information about spacecraft surface deposition (*i.e.*, distribution and velocity of discharge chamber erosion products in the plume) and/or erosion. However, it is the long-duration nature of these tests that prevents researchers from "taking risks" and performing probe-based diagnostics. Non-intrusive techniques for mapping erosion products in the plume would alleviate this problem.

What is needed, therefore, is a method for measuring thruster erosion rates non-intrusively, in real- or near-real-time, and yet provides information about the ions that are eroding the insulator and the distribution and trajectory of eroded thruster material in the plume. As the summary below describes, the equipment requested in this DURIP proposal should satisfy these criteria.

Summary of DURIP Purchases

DURIP funds were sought and used to purchase the following items :

1) A tunable diode laser for making infrared (IR) laser induced fluorescence (LIF) measurements of Xe atoms and ions;

2) A dye-to-Ti:sapphire conversion kit for PEPL's Coherent 899-29 Autoscan II ring dye laser for IR measurements of boron nitride, the primary constituent of SPT discharge chamber insulators; and

3) Internal cryopumps to increase the pumping speed of PEPL's 6 by 9 m vacuum chamber by more than 50% (from 140,000 l/s to 240,000 l/s).

4) Acommercial ion sputtering source

5) Miscellaneous optical and vacuum supplies for diagnostics and vacuum facilities enhancement.

The tunable diode laser and converted 899-29 Ti:sapphire laser will establish a capability for making non-intrusive Hall thruster erosion measurements in near-real-time by simultaneously exciting xenon and boron nitride transitions at a spot within the engine or in the plume. This is made possible by using separate input laser wavelengths for exciting the xenon and boron nitride, and using phase sensitive detection methods to detect the fluorescence output signals of both species. This capability will not only enhance an already impressive array of diagnostics at PEPL, but will establish a national facility where thruster erosion and spacecraft integration issues are investigated. Moreover, the combination of our current UV-capable ring dye laser, the diode laser, and the dye-to-Ti:sapphire conversion kit will enable the simultaneous measurement of thruster erosion products such as boron nitride (IR) or refractory metals (UV using a dye) with neutral (visible, IR) or ionized xenon (visible, IR), or the simultaneous measurement of two xenon ionization states (visible, IR, UV). The ability to measure both the erosion rate and the local plasma flowfield will provide an unprecedented understanding of erosion physics. Moreover, the ability to track xenon neutrals and ions simultaneously with thruster erosion products in the plume will contribute greatly to our understanding of particle transport as it relates to spacecraft surface deposition of thruster erosion products.

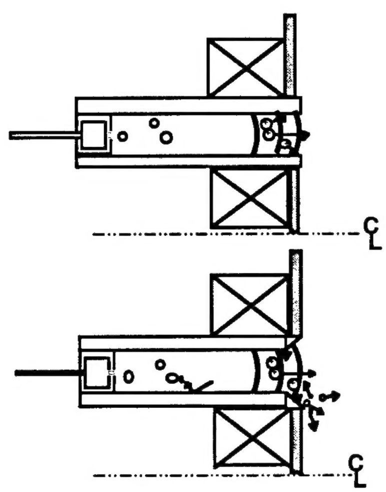


Figure 2: Illustration of discharge chamber wall erosion. Top image shows a new insulator while the bottom image shows one subjected to erosion. Curvature in the electric field causes ions to impact the wall. Sputter wall material way deposit on spacecraft surfaces, re-deposit within the engine, or become ionized and accelerated.

A critical requirement for this capability is to have a vacuum facility of high pumping speed and sufficient volume to minimize facility effects. This will be more important and difficult to achieve as thruster size and power continue to increase. Anticipating the DoD's need for growth in thruster power, funds were requested and used to purchase three internal cryopumps for the 9 by 6 meter vacuum chamber at PEPL. These pumps will increase the xenon pumping speed from 140,000 l/s to 240,000 l/s, enabling higher-power (5-20 kW) Hall thrusters to be operated at sufficiently low back pressures to permit high-fidelity spacecraft integration studies, laser-based thruster erosion measurements, and advanced thruster development programs to take place.

Equipment Purchased from DURIP Funds

DURIP funds were used to purchase a xenon cryopumping system and an LIF system to enhance greatly PEPL's capability to perform EP spacecraft integration and development research. Each of the purchased systems are described below.

Cryopumping System

Table I showing the various tank pressures which are required for certain EP research activities is presented below for the sake of convenience. In general, chamber pressures of 10^{-5} Torr or less are desirable for spacecraft integration work. In order to achieve this pressure, large pumping speeds are necessary. For example, in order to maintain a pressure of 10^{-5} Torr with an SPT-100 (5 mg/s of xenon), the vacuum facility would have to have a xenon pumping speed of over 70,000 l/s. Thus, in order to operate a 5-kW-class Hall thruster at this same pressure, a pumping speed of over 100,000 l/s is necessary.

There are several means of achieving this level of pumping speed. A large gaseous He refrigeration system with LN_2 cryopanels - the kind currently used at NASA GRC - is prohibitively expensive for any university. Another approach is to use a bank of diffusion pumps or cryotubs. Oil diffusion pumps are somewhat ineffective on xenon and pose the danger of thruster contamination due to oil backstreaming. As an example, Tank 5's twenty 0.8-m-diameter diffusion pumps for a combined pumping speed of only 90,000 l/s versus nearly 2 million l/s from its bank of cryopanels.[19] Thus, over forty 0.8-m-diameter diffusion pumps would be required to reach 100,000 l/s on xenon. Further, if one minimizes backstreaming with cryo-baffles and cold-traps, pumping speed suffers greatly. To achieve a pumping speed of over 100,000 l/s on xenon with conventional cryotubs, several 1.2-m-diameter units would be necessary, at a cost of at least $80,000 each when required facility modifications are taken into account. Moreover, consumables (LN_2 and/or diffusion pump oil) are required for all of the pumping scenarios above, the cost of which, particularly the LN_2, can reach several hundred dollars a day.

Table I: Required chamber pressure as a function of research activity for the Hall thruster and arcjet from the analysis of Reference [27].

Activity	Hall Thruster	Arcjet
Performance	5.0E-05 Torr	5.0E-02 Torr
EMI	5.0E-05 Torr	5.0E-05 Torr
Intermediate Plume	1.3E-05 Torr	1.3E-05 Torr
Life	5.0E-06 Torr	unknown

Therefore, a cryopumping system is needed that requires little or no consumables, and provides high performance in a cost effective manner. In addition, such a system should be robust and modular, so that segments of the system can be removed for repair or refurbishment without taking the entire system off-

line. The system that had been identified which would satisfy these requirements is a bank of gaseous He cold-heads. However, the technological maturity of such a system was not sufficient at the time, and the cost was much higher than anticipated. It should be noted that such a system could be used to augment the xenon cryopumping system that was actually purchased.

The system that was purchased consists of three CVI TM-1200 nude (reentry) cryopumps to augment the four already installed on the LVTF. These are the same pumps used for CVI's 1.2 m cryotub, however the sail is enclosed within a box with three louvered sides. The entire box is placed within the vacuum chamber. Because of the low conductance losses associated with this configuration in comparison to conventional tubs, each pump has twice the pumping speed of its conventional counterpart (35,000 l/s vs. 15,000 l/s on xenon). A number of benchmark tests were performed to measure the pumping speed of the facility.

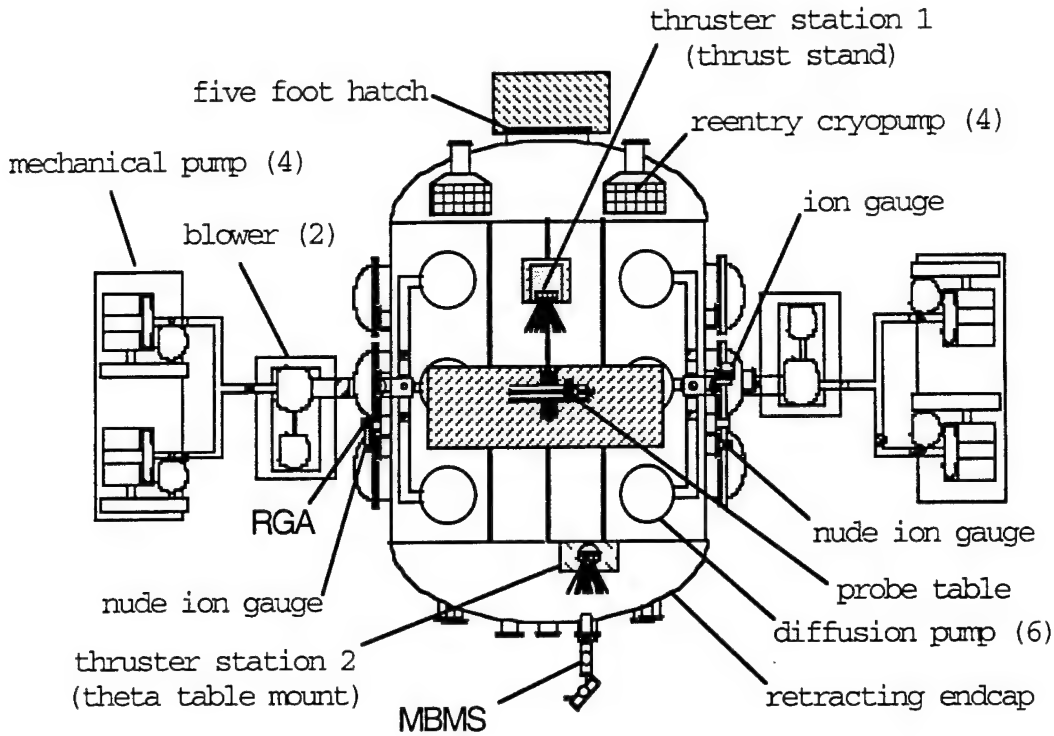
Garner Facility Services, Inc. was hired out of University of Michigan cost-sharing funds to be the general contractor of the work. The xenon pumping speed with all seven pumps was measured at approximately 240,000 l/s and the nitrogen pumping speed at 520,000 l/s. The base pressure of the facility is ~1 x 10^{-7} Torr. A sketch of the LVTF prior to and after the recent modifications is shown in Fig. 3.

LIF System

Laser-Induced Fluorescence (LIF) has become a staple in the diagnostics suite of electric propulsion research.[26,27] The basic principle behind LIF is quite simple. Coherent laser light that is tuned to a wavelength of a particular transition of interest illuminates a selected volume of the plume. The tuned laser light excites a molecule, initiating an electronic transition to an upper state. Some of these molecules radiatively decay and emit radiation at or near the wavelength of the incident laser light. This radiation is then collected and analyzed to determine certain attributes of the plume gas. For example, LIF can be used to measure heavy particle translational temperature by looking at the Doppler broadening of a line (transition). Since translational is nothing more than a reference to the random velocity distribution of constituents, Doppler broadening - a measure of the integrated Doppler "shifts" due to random particle motion - is as direct a means of measuring this quantity as is possible. Further, by adjusting the optics appropriately, LIF can be used to measure the bulk velocity of the plume by measuring the total Doppler shift of the laser in a particular direction.[28] LIF can also be used to measure electron number density through stark broadening, species concentrations, and the distribution of energy states for a particular substance.[29]

Although LIF has been applied to EP diagnostics with great success, the vast majority of these measurements have taken place at background pressures which almost certainly impact the thruster operation, and therefore, the fidelity of the measurements. For example, LIF measurements with arcjets to date have taken place in chambers with pressures between 55 mtorr and over 1 Torr.[28] As attractive as it is to characterize flowfield with non-intrusive means, it is imperative that these measurements take place at pressures which will not affect the flow. For example, the pressure in one study was so high that the evidence of shocks existing in the plume was seen. For this case, the flow was observed to decelerate after a certain distance from the thruster plane, an obvious artifact due to the existence of shocks. Thus, with the exception of NASA GRC, AFRL, and possibly the Aerospace Corporation, no other EP experimental facility in the nation of adequate pumping speed is equipped to perform LIF measurements on Hall thrusters.

a)



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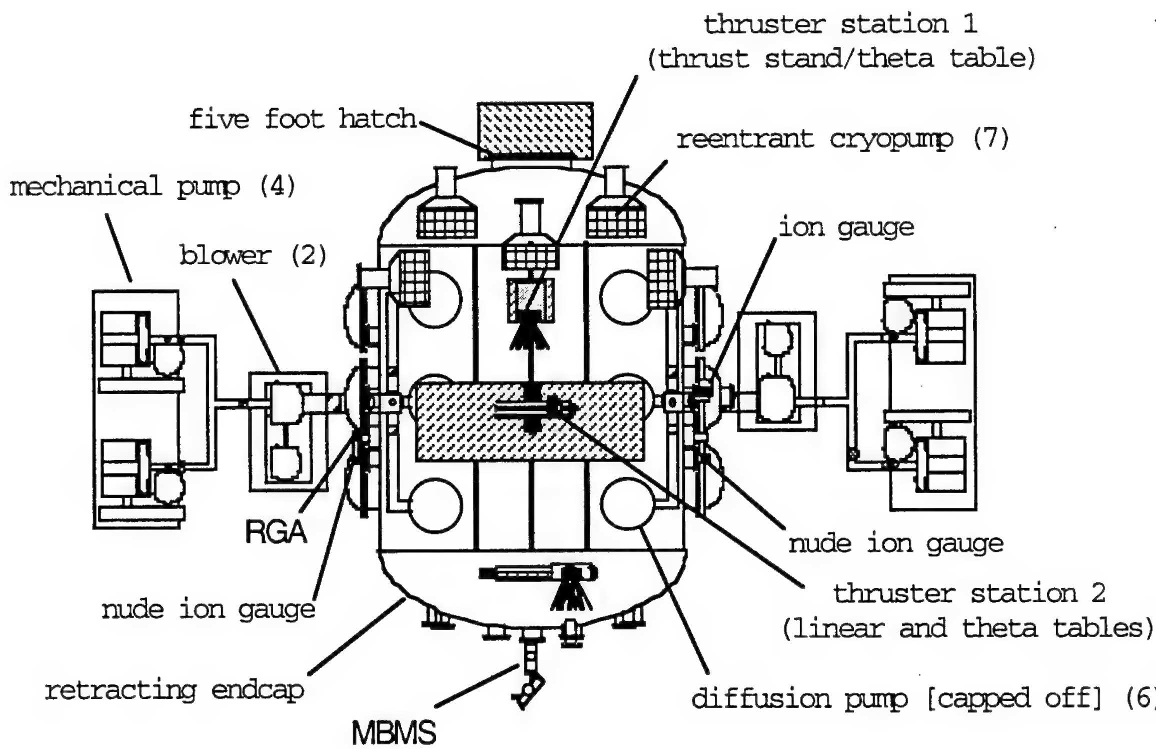

Figure 3: Large Vacuum Test Facility a) in 2000 with four cryopumps and a xenon pumping speed of 140,000 l/s; and b) in 2002 with with seven cryopumps and a xenon pumping speed of 240,000 l/s

In 1998, DURIP funds were used to purchase two lasers - a pump laser and a ring dye laser - which comprise the bulk of a new laser diagnostics facility at PEPL. The Coherent model 899-29 Autoscan II ring dye laser is capable of outputting light within a spectral range of 375 nm - 900 nm (with appropriate dyes) with a linewidth of less than 500 kHz rms. The single frequency ring laser is computer controlled and has a wavelength meter attached to it which measures the laser frequency within ±200 MHz (0.0067 cm^{-1}). This laser is capable of incorporating a frequency doubler as well as a Dye-to-Ti:Sapphire conversion kit, the latter which was purchased in the most recent DURIP. The dye laser will be pumped by a Coherent Innova 400-15 argon ion laser. The pump laser produces 15 W of power on all measurement spectral lines. This pump laser should enable the dye laser to generate several hundred milliwatts of power over the spectral range of interest.

The 2000 DURIP was used to purchase a high-power (500 mW), single-frequency, continuously tunable TA 100 diode laser by TUI-OPTICS of Martinsried, Germany. This particular diode laser can readily interrogate Xe, Xe^+ and any as yet unspecified transitions between 825 and 875 nm. The ring and diode lasers can be configured to interrogate the same spot simultaneously (see next section). This would allow for two different species to be characterized at the same location and time; *e.g.*, Xe and Xe^+, or Mo and Xe^+. The diode laser system would scan for Xe or Xe^+ while the dye- or Ti:sapphire-configured ring laser would scan for the second species.

Simultaneous Measurement

A simultaneous dual-wavelength LIF technique is crucial for identifying the source, energy, and relative density of ions causing discharge chamber erosion and correlating this information with insulator erosion rates as a function of chamber pressure. Simultaneous measurement of the ion energy and component erosion would provide a direct near-real-time[&] correlation with the operating condition. A dual-wavelength method is required because transitions associated with neutral xenon (Xe), xenon ions (Xe^+) and (Xe^{++}), and eroded materials (BN) are different.

Simultaneous ion and neutral LIF measurements would provide knowledge about Xe-Xe^+ charge exchange collisions and would give an indication of the ionization fraction at a given location within the thruster or in the plume. The ability to measure both of these in the infrared (IR) significantly reduces the complexity of the delivery optics. The ratio of singly- to doubly-charged ions, similarly, relates to thruster efficiency since CDTs operate best and are less damaged and less destructive to the spacecraft when the fraction of doubly-ionized xenon is minimized. Moreover, our research has shown that CDTs emit not only Xe, Xe^+, and Xe^{++}, but Xe^{3+}, and Xe^{4+} as well.[24,30] Double-charged xenon ions have been identified as a primary source of grid and cathode erosion in ion thrusters[31]. Simultaneous measurement of any two species would enable a real-time correlation between them and would provide insight to the role that multiply-ionized xenon particles have on CDT erosion. It is therefore important to study the mechanisms which lead to insulator erosion in order for pressure correction tools to be developed. Since the P5 is an SPT (*i.e.*, with insulator walls), we will concentrate our effort on understanding Boron Nitride erosion physics.

Boron Nitride Erosion

Boron nitride erosion in CDTs potentially reduces thruster and spacecraft lifetime and degrades thruster performance. As stated above, quantifying the rate of erosion and understanding how tank pressure affects erosion are critical to thruster design and spacecraft integration. Gaeta *et al.*[32,33] have shown that LIF of

[&] "near-real-time" limitation is dictated only by the necessary laser scanning duration (*e.g.*, 15 seconds)

neutral molybdenum can be used as an erosion rate diagnostic for ion thrusters. We have recently successfully employed this technique to measure the erosion rate of the discharge cathode orifice plate of an NSTAR-derivative ion thruster. Lorenz *et al.*[34] showed that near-IR transitions (1.04 and 1.53 micron) of BN are strongly excited by 816.5 nm light. These studies suggest LIF may be used as a real-time diagnostic of the erosion rate of CDT discharge chambers and to investigate facility effects on erosion. Correlating this erosion rate with LIF measurements of xenon neutral (Xe) and ion (Xe^+, Xe^{++}) velocity distributions may indicate the physical processes underlying discharge chamber erosion and the transport of erosion products throughout the plume. However, this capability would require simultaneous LIF measurement of xenon ion energies and BN density.

We would extend our current 3-component multiplex LIF system which allows simultaneous interrogation of the probe volume by 3 laser beams to a second laser since this approach can be extended to an arbitrary number of beams. These additional beams need only be parallel to the focusing lens axis, chopped at controlled frequencies, and approximately equidistant from the lens axis (to avoid spherical aberration problems). The key to our approach is that these beams <u>do not</u> need to have the same wavelength, nor do they have to excite the same transition.

To provide both measurement capacities described above, DURIP funds were requested and granted recently to purchase a single-frequency, tunable diode laser and a Ti:sapphire conversion kit for our existing ring dye laser. The combination of dye, Ti:sapphire, and diode lasers would provide the following unique capabilities:

- The ability to measure erosion rates and the velocities of ions causing this erosion on laboratory-model and flight-quality Hall thrusters (both SPTs and TALs);

- The ability to simultaneously measure charge exchange neutrals and ions both within the thruster discharge chamber and throughout the plume;

- The ability to conduct simultaneous internal and external measurements;

- The ability to measure Xe and Xe^+, Xe and Xe^{++}, or Xe^+ and Xe^{++} simultaneously at the same location;

- The ability to determine the degree of plasma thermodynamic equilibrium; and

- The ability to measure Xe or Xe^+ temperatures and velocities more precisely, giving two independent, simultaneous measurements.

Because of the complexity of the erosion process, our investigation will initially focus on thruster erosion physics in low-background pressures. The investigation will then be extended to higher tank pressure once we are confident that we have identified the fundamental mechanisms for discharge chamber erosion. We will first utilize a proof-of-concept experiment (currently underway) in a smaller vacuum facility that utilizes a commercial ion sputtering source and a BN slab. Once the technique has been mastered in the proof-of-concept apparatus, it will be ported over to the LVTF for testing with the P5 CDT.

<u>Major Purchase Items from DURIP Fund</u>

3	CVI TM-1200 Nude Cryopumps (each 35,000 l/s xenon, 75,000 l/s nitrogen)
	Garner Facility Services, Inc. was hired as general contractor to install pumping system
1	Coherent Ta:sapphire conversion kit for Coherent Model 899-29 ring laser system
1	TuiOptics TA100 tunable diode laser

1 Hiden Langmuir probe system

1 Commonwealth Scientific 3-cm commercial ion source

Assorted equipment for laser system and chamber modification.

Total Funds from DURIP:	\$248,011
Total Funds from Michigan:	\$75.000
Total Funds for Project:	**\$323,011**

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